FPRINT-94-71

Fermilab Library
0 1160 0054327 4

FPRINT-94-71

FERMILAB
DEC 7 199
LIBRARY

Paper given at Tokyo Workshop - May 1994
"Towards a Major Atmospheric Čerenkov Detector - III"

C94/05/25.3

VHE γ-ray Astronomy and Other Fields - The Sources of High Energy Cosmic Rays

R.C. Lamb
Physics and Astronomy Department, Iowa State University, Ames, Iowa 50011, USA

Abstract

This paper examines the context of VHE γ-ray astronomy, its relevance to other branches of photon astronomy, particularly that which is now being explored by the Compton Gamma Ray Observatory at lower energies, and focuses on the role of VHE γ-ray astronomy in establishing possible galactic and extragalactic sources of cosmic rays.

1. Introduction & Scientific Motivation

For comprehensive, up-to-date reviews of the field the reader is referred to articles contained in the proceedings of last year's Calgary workshop (Raubenheimer 1993; Fontaine 1993; Goret 1993) and contributions presented at this workshop: Aharonian on the relationship between VHE γ-rays and the EGRET sources and Goret's rapporteur talk summarizing the status of VHE γ-ray astronomy.

A VHE γ-ray astronomer must have something of a split personality. On the one hand we now point to a source list which includes dozens of sources, and proclaim to ourselves and our colleaques in related astronomies that TeV astronomy has "come of age". While it is demonstrably true that substantial progress in this field has been made, I suspect that for many of us *the prime motivation continues to be that the sky between 30 GeV and 100 TeV is a largely unexplored frontier with virtually all of its discoveries yet to be found.* Because of the successes of the Compton Gamma Ray Observatory some of the future discoveries may now be reasonably extrapolated from its experience, and, in the next sections, some of these "predictable" discoveries will be discussed. However, the allure of the unknown and unexpected remains a powerful motivator for this field.

One of the long-standing prime objectives for VHE γ-ray astronomy is the desire to establish direct evidence for the sources of cosmic rays. If the sources of very-high and ultra-high energy cosmic rays are extragalactic at distances more than twice the distance to the Virgo cluster (20 Mpc) then the photon window for their exploration effectively closes above 10^{14} eV. (See section 2.4 below on the role of intergalactic absorption.) Thus VHE γ-ray

astronomy has the potential to view the highest photon energy at which distant extragalactic cosmic-ray sources may be studied directly.

It is well established that the cosmic-ray spectrum extends to 10^{20} eV yet the origins of such spectacularly high energy particles remains obscure. Particle energies of this magnitude imply that near their acceleration sites a range of elementary particle physics phenomena is present which is beyond the ability of present-day particle accelerators to explore. VHE γ-ray astronomy may catch a glimpse of such phenomena.

It is becoming increasingly clear that the energy regime covered by VHE γ-ray astronomy will be able to address a number of significant scientific questions. A partial list of them includes:

- What parameters determine the cut-off energy for pulsed γ-rays from pulsars (section 2.5.1)?
- What is the role of shell-type supernovae in the production of cosmic rays (section 2.5.2)?
- At what energies do AGN blazar spectra cut-off (section 2.3)?
- Are γ blazar spectral cut-offs intrinsic to the source or due to intergalactic absorption (sections 2.3 and 2.4)?
- Is the dominant particle species in AGN jets leptonic or hadronic (section 2.3)?
- Can intergalactic absorption of the VHE emission of AGN's be a tool to calibrate the epoch of galaxy formation, the Hubble parameter (section 2.4), and the distance to γ-ray bursts (section 2.6)?
- Are there sources of γ-rays which are "loud" at VHE energies, but "quiet" at other wavelengths (section 2.7)?

2. Possible Sources of Cosmic Rays

2.1. Overview

The final figure of Teshima's rapporteur talk at the Calgary Cosmic Ray Conference (Teshima 1993), shown here as figure 1, provides an excellent summary of the current view of the origins of cosmic rays. The arguments leading to this decomposition are indirect. At energies to 10^{14-15} eV galactic supernova remnant shocks are the most plausable site for nucleonic cosmic-ray acceleration. There are reasons for optimism that future VHE γ-ray observations will produce direct evidence for their expected contributions. (See section 2.5.2 below.) Above 10^{14-15} eV other sources must be sought, and the figure gives two possibilities. At the highest energies, 10^{18-19} eV and above, several arguments are presented which lead to the conclusion that the dominant sources of such particles are extragalactic.

In figure 2 four possible scenarios for the production of γ-rays are illustrated. In both a) and b) the gamma-rays are produced within the galaxy; for case a) it is a two-step process in which a cosmic-ray from a galactic source produces a γ-ray by interacting with galactic matter at some distance from the source. For case b) the γ-ray is produced directly at the source. (In both cases, the source could be accelerating nucleons, or electrons, or both.) For cases c) and d) the sources of γ-rays/charged particles are assumed to be extragalactic.

With the detection of several galactic sources and one firm extragalactic source (Markarian 421) VHE γ-ray astronomy has already produced evidence for processes b) and d). EGRET and its predecessor satellite detectors, SAS-2 and COS-B, have detected process a), but failed to detect process c). This failure is one of the indicators that for cosmic ray energies below $\sim 10^{11}$ eV the bulk of cosmic rays are galactic.

2.2. EGRET - The All-sky Survey

The EGRET team has compiled an all-sky source catalog of 124 sources (Fichtel *et al.* 1994). Forty-two are within 10° of the galactic plane. Aproximately half of the out-of-plane sources are identified with AGN's, and there is a reasonable presumption that many of those

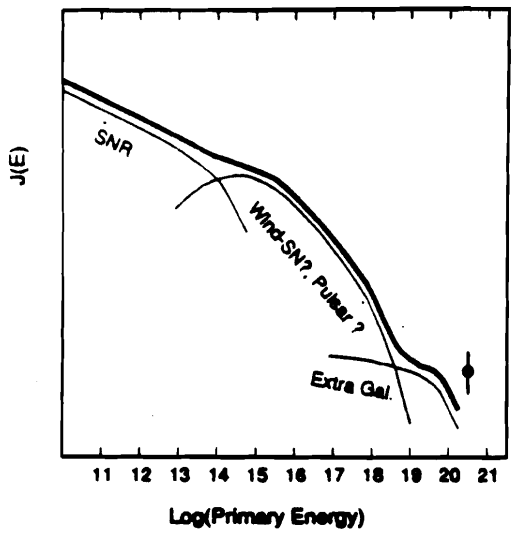

Fig. 1. Schematic figure of the cosmic ray total energy spectrum (from Teshima 1993).

remaining $|b| \geq 10°$ sources will be identified ultimately as AGN's. In constrast, only 5 of the EGRET in-plane sources are firmly identified (with pulsars). Some of the unidentified in-plane sources are probably associated with supernova remnants as discussed below in section 2.5.2.

The EGRET detector has provided dramatic evidence for the process illustrated in figure 2 a) in which a cosmic ray (presumed galactic) interacts with the galactic matter density to produce a high energy γ-ray. One sees clearly this process at work in figure 3, an all-sky view in the light of photons with energies above 100 MeV. The brillant band of emission corresponds to the plane of the galaxy. What fraction of this flux can be attributed to a superposition of point-like sources is uncertain. One estimate of point-like contributions to the galactic disk emission is as low as 8% (Bloemen 1993), whereas a different set of assumptions leads to an estimate of 50% (Bailes and Kniffen 1992).

At the present time, the only direct evidence that γ-ray astronomy brings to the question of the origins of nucleonic cosmic-rays is taken from the EGRET detector's upper limit on the flux of γ-rays from the Small Magellanic cloud (Shreekumar *et al.* 1993). This process is illustrated in figure 2 c). If low energy cosmic rays ($\leq 10^{11}$ eV) are extragalactic then their intensity at the SMC is the same as within the galaxy. This leads to a definite prediction of the flux of photons >100 Mev (Chi and Wolfendale 1993, Sreekumar and Fichtel 1991) which is several times what is observed. Thus the conclusion (albeit not very strong) is that for the lowest energy cosmic rays (up to $\sim 10^{11}$ eV) the cosmic ray flux is mainly galactic.

2.3. EGRET - Active Galactic Nuclei

One of the major successes of the Compton Gamma Ray Observatory is the discovery of high energy gamma rays from AGN's. The number of identified AGN's from the first EGRET catalog (Fichtel *et al.* 1994) now stands at 38. At other wavelengths, these sources are all bright, flat spectrum radio sources, with, in many cases, optical polarization and rapid optical variability, charateristics of the blazar class of AGN. (Dermer and Schlickeiser (1992) and Antonucci (1993) are useful guides to AGN taxonomy. In the simplest, unified picture of the AGN phenomena, blazars are those AGN's which have associated jets with the jet axis oriented near the observer's line-of-sight.)

The gamma-ray luminosities inferred from the EGRET observations are in the range of 10^{44} to more than 10^{49} ergs/s if one assumes isotropy. However, the true luminosities will be several orders of magnitude less if the gamma-rays are associated in some way with the relativistic jets of the blazars and are thereby beamed. Most models that have been advanced

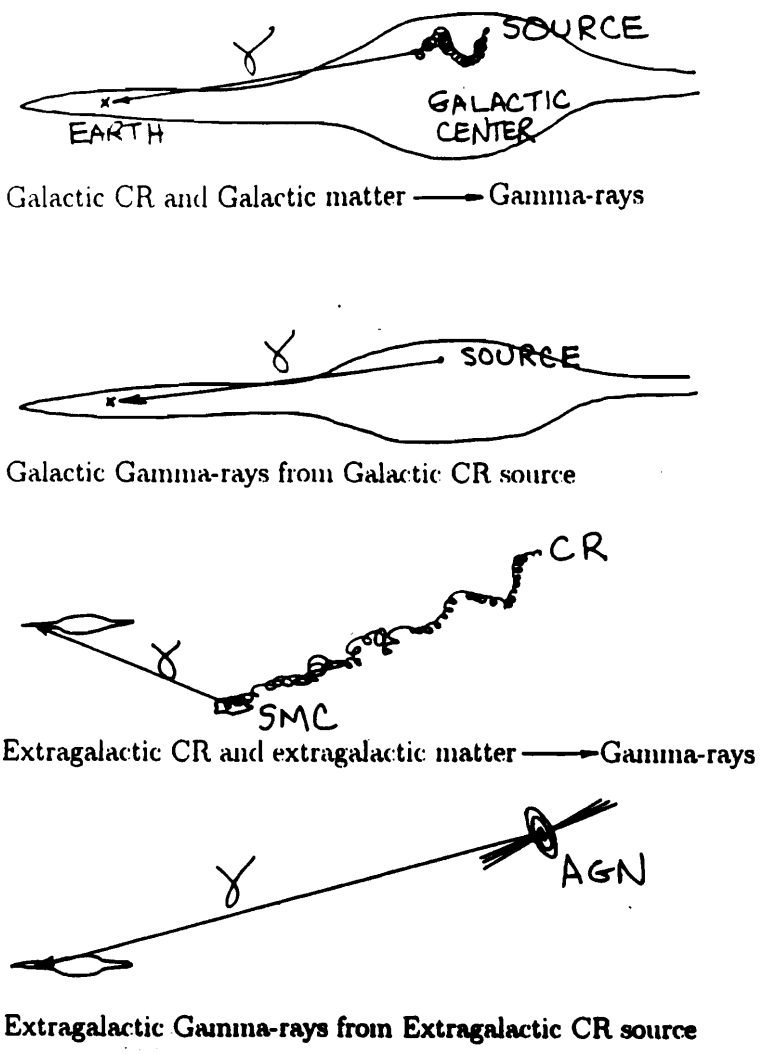

Fig. 2. Schematic diagrams of 4 possible scenarios for gamma-ray production.

to account for the gamma-rays make this assumption.

The spectra of the EGRET-detected AGN's are well represented by power-laws with photon differential indices in the range of 1.5 to 2.6 (Hartman *et al.* 1994). There is little or no evidence for a break in the spectra at the highest energies achieved by EGRET, which, even for the brightest AGN's is effectively 10 GeV. (Note: Only 2-3 detected photons above 10 GeV are expected for a moderately bright EGRET source during a typical 2-week EGRET observation, assuming a flux above 100 MeV of 10^{-6} photons/cm^2/s and differential index of 2.0.)

One of the principal observational questions connected with the AGN's is their spectral cut-off. At the present time, it may well be that many of the AGN's have spectral cut-offs that are intrinsic (*i. e.* not caused by intergalactic absorption) and are effectively below the present threshold of VHE γ-ray detectors ($\sim$ 250 GeV). This presents a strong incentive to reduce the threshold of VHE detectors so that this regime can be explored.

The origin of the AGN gamma-ray emission is currently a subject of much theoretical debate. In one school of thought, the γ-ray emission from blazars involves inverse Compton scattering of lower frequency "seed" photons from high energy electrons in the inner regions of a relativistically flowing jet aimed almost directly along the line-of-sight. Some of these

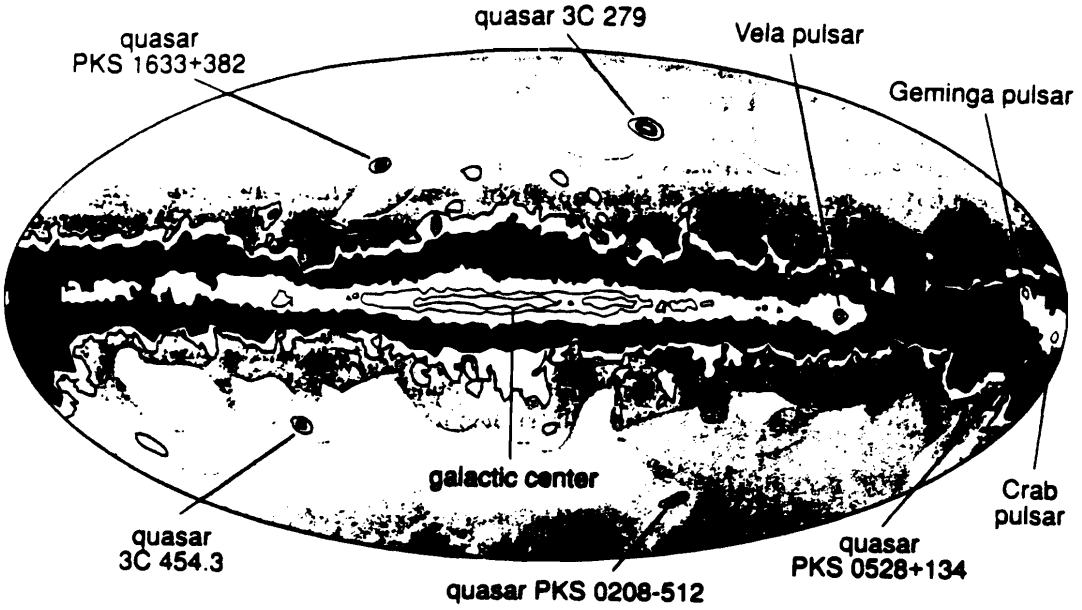

Fig. 3. A full-sky view by the EGRET detector for photons with energies $\geq$100 MeV (taken from Kniffen 1993)

models predict a cut-off to the spectrum in the range 10 - 100 GeV. An example of such a model is that of Sikora, Begelman, and Rees (1994). The spectrum of 3C 279 showing the predicted cut-off in the region above 10 GeV is shown in figure 5. If, on the other hand, the γ-rays result from secondary pion production (Mannheim 1993) then one expects a hardening of the spectrum above 10 GeV. This distinction between the "leptonic" versus "hadronic" beam models presents the VHE γ-ray astronomy community with an opportunity for decisive observations, if the energy threshold of our instruments can be lowered sufficiently to probe to 10 GeV. However, the issue of the identity of the dominant jet constituent may well await the day of sensitive VHE neutrino detectors. If the jets are predominantly hadronic then neutrinos will be present with fluxes comparable to γ-ray fluxes, whereas if the jets are predominantly leptonic then the neutrino production will be greatly supressed.

The detection of Markarian 421 (Punch *et al.* 1992) and its continuing monitoring by the Whipple Observatory (Schubnell *et al.* 1994, Kerrick *et al.* 1994) has made it clear that not all of the γ-ray blazars are cut-off below the threshold of present-day VHE γ-ray detectors. Its energy flux (kev/cm^2/s) (from Zdziarski and Krolik 1993) is plotted in figure 6.

As energy thresholds are lowered and sensitivities of VHE γ-ray instruments improved, other EGRET detected AGN's will be detected. Even at present VHE sensitivity levels, there is the possibility that some AGN's are detectable now at VHE energies, but because of their hard spectra they are undetectable at EGRET energies.

Many questions remain. For example, where in the jets do the gamma-rays originate? In the inverse Compton scattering model proposed by Blandford and Levinson (1994), there is an approximate energy-distance mapping such that the more energetic photons come from greater distances from the central engine. The minimum variability time scale of high-energy gamma rays therefore limits the size of the gamma-ray emitting region. A consequence of this prediction is that the typical variability timescale ought to lengthen with increasing gamma-ray energy. Therefore, if time variations are seen in the 100 GeV-multi-TeV regime and if this model is correct, one should expect even more rapid variations at EGRET energies.

As stressed by Bregman (1992), Marscher (1993), and Blandford and Levinson (1994),

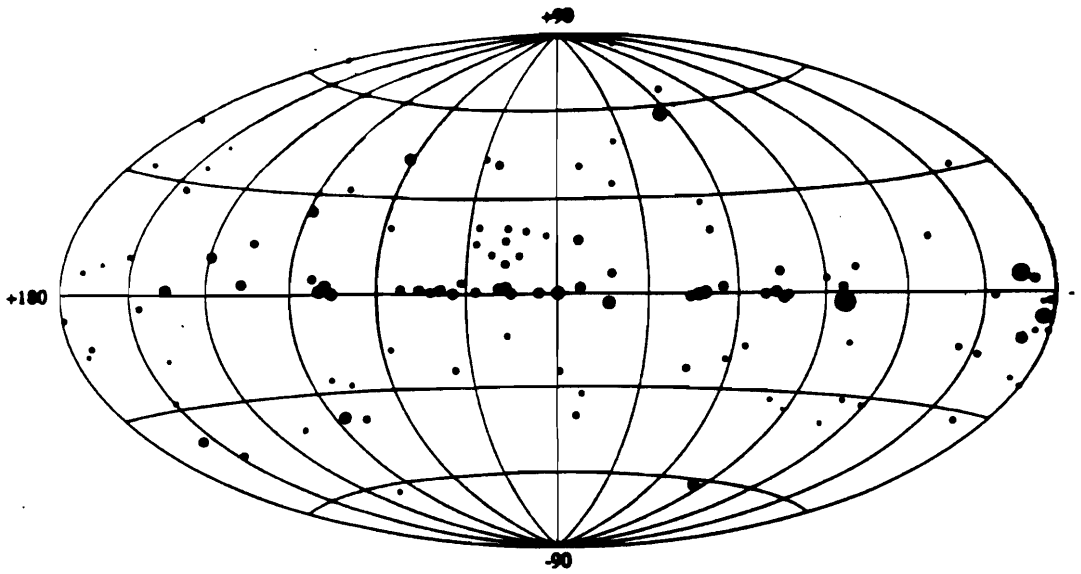

Fig. 4. Location of point-like sources given in the first all-sky survey by the EGRET detector (Fichtel *et al.* 1994). The area of each circle is proportional to the source flux.

multiwaveband observations of flares in blazars currently hold the greatest promise for exploring the region where the relativistic plasma is generated and the jet focused and accelerated. Particularly relevant is the correlation between the mm/submm radiation and the GeV/TeV emission. By measuring time delays of variations in brightness as a function of frequency, it may be possible to constrain the geometry of the inner jet as well as infer the steepness of gradients in magnetic field, relativistic electron density, and bulk Lorentz factor of the jet flow (e.g., Marscher 1993).

The recent outburst of Markarian 421 (Kerrick *et al.* 1994) in which its flux above 250 GeV increased by ~10 in a matter of days raises the possibility of future correlated broadband, multiwavelength observations for this object which can address the issues described above.

2.4. Intergalactic Absorption

The dominant absorption mechanism for VHE photons as they traverse the intergalactic medium is pair production against low-energy photons associated with the intergalactic starlight field. This process, first considered by Gould and Schréder (1966) and, more recently by Stecker, de Jager, and Salamon (1992), produces an attenuation of VHE photons which depends heavily on what one assumes about the density of starlight photons. In principle this is calculable from what is known about the starlight and dust content of galaxies and the time at which galaxies first formed.

Such a calculation has recently been performed by MacMinn and Primack (1994) who show that the spectrum from a source will exhibit a broad absorption dip whose depth and precise shape is dependent on the epoch of galaxy formation. Figure 7 gives an example of the amount of spectral modulation to be expected for a z=0.2 object, using reasonable values of the parameters. Thus, if there are several AGN's whose intrinsic spectra reach beyond 10 TeV (a big "if" it would seem at the present time), then careful measurements of their spectra over at least 3 decades in energy in the VHE range may provide constraints on the epoch of galaxy formation.

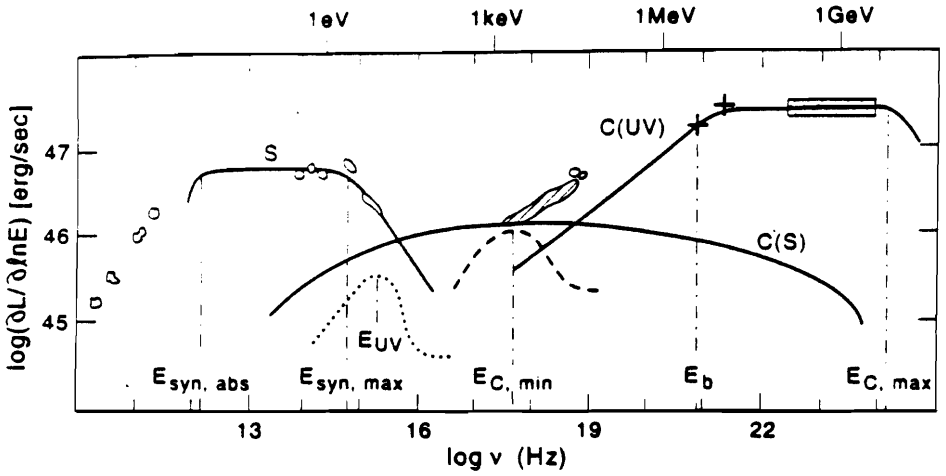

Fig. 5. The energy flux from 3C 279 (from Sikora, Begelman, and Rees 1994). Solid lines mark the model spectrum. S = synchrotron radiation; C(S) = Comptonized synchrotron radiation; and C(UV) = Comptonized diffuse UV radiation.

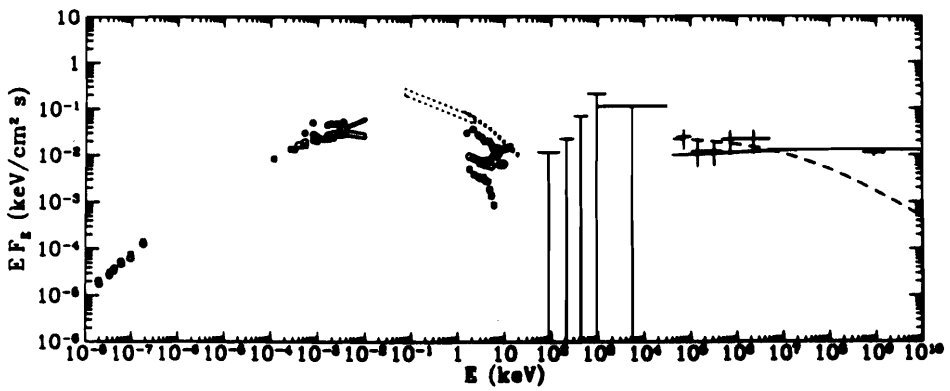

Fig. 6. The energy flux from Markarian 421 (from Zdziarski and Krolik 1993). The high energy observations are those of EGRET (Lin *et al.* 1992); the VHE observation is that of the Whipple collaboration (Punch *et al.* 1992).

A somewhat more ambitious use of the intergalactic attenuation of AGN γ-rays is a proposal to extract the Hubble parameter from a study of the extinction of AGN spectra at various redshifts (Salamon, Stecker, and de Jager 1994). The method depends on the presence of the Hubble parameter in the relationship between optical depth and redshift. For the method to be successful many AGN's must be detected and their intrinsic spectra must extend to energies well above 1 TeV.

2.5. Galactic Sources

2.5.1. Pulsars

Six spin-powered pulsars have been seen by the Compton Gamma Ray Observatory: Crab, Vela, Geminga, PSR B1055-52, PSR B1509-58, and PSR B1706-44. PSR B1509-58 was detected by the OSSE instrument, the others by EGRET. It is notable that of two of the firmly established TeV sources are on this list, the Crab Nebula and PSR B1706-44 (Kifune *et al.* 1994). As EGRET increases its exposure to the galactic plane, further discoveries of γ-ray pulsars are likely and they become prime candidates for VHE emission as well. It is also possible that some of the presently unidentified EGRET galactic sources are pulsars, not

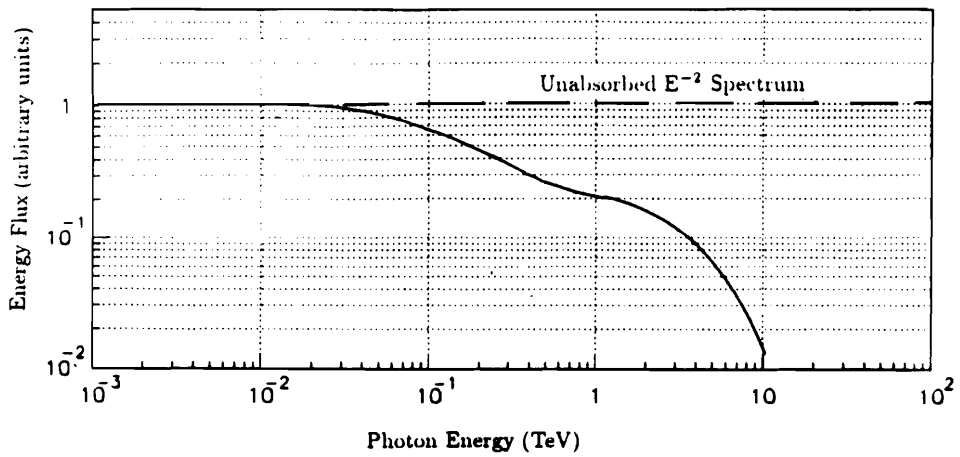

Fig. 7. Modulation to an assumed power-law spectrum from an AGN at z=0.2 (taken from MacMinn and Primack 1994). The dip is due to the absorption of the VHE photons by intergalactic photons red-shifted from the visible to the infrared. The depth and shape of the amount of absorption are dependent on the precise epoch at which galaxies first formed.

yet detected as radio pulsars because of sensitivity limits or beaming effects (see the following section).

Two questions concerning the Crab pulsar and its Nebula are already addressed by a combination of EGRET and VHE observations. One question is the precise value of the energy above which pulsations cease. Previous reports of pulsations by the Durham group (Dowthwaite *et al.* 1984) above 1 TeV, but only upper limits by the Whipple group (Vacanti *et al.*1991) above 400 GeV, suggest that the limiting energy for pulsation is time dependent, and that all Crab Nebula observers should therefore check routinely for the presence of pulsations. For those cases where TeV pulsations are observed, then one can say that the pulsed photons must be produced in a region relatively far from the surface of the neutron star, where the magnetic field is weak. Otherwise the high energy photons will be absorbed as they interact with the virtual quanta of the magnetic field to produce electron-positron pairs.

Another question relates to the shape of the unpulsed spectrum. De Jager *et al.* (1994) have a synchrotron self-Compton model for the unpulsed spectrum which provides a nice interpretation to both the EGRET data and the VHE data. A current fit to the data of their model is shown in figure 8. Although there is a gap in the data between the highest energy EGRET points and the lowest VHE points, one could say that the model is well constrained. What is needed here are similar curves for all of the γ-ray pulsars. Then one could begin to address the question of what are the relevant parameters that govern the unpulsed component of pulsar γ-ray emission.

Although γ-rays from these objects most probably originate in the interaction of relativistic electrons with synchrotron photons within the pulsar nebula, the acceleration sites and processes for electrons and hadrons must be closely related. Thus the observation of TeV photons from such pulsar-driven supernova remnants is confirmation that high energy acceleration processes can be associated with the aftermath of supernova explosions.

2.5.2. Unidentified Galactic Sources and Shell-type Supernovae

Thirty seven of the 42 galactic plane sources reported in the first EGRET catalog are unidentified. This situation is reminiscent of the condition of high energy gamma-ray astronomy following the publication of the COS-B catalog (Swanenburg *et al.* 1981). Approximately 90% of its in-plane sources were unidentified.

Many papers, both observational and theoretical, have been written in an attempt to

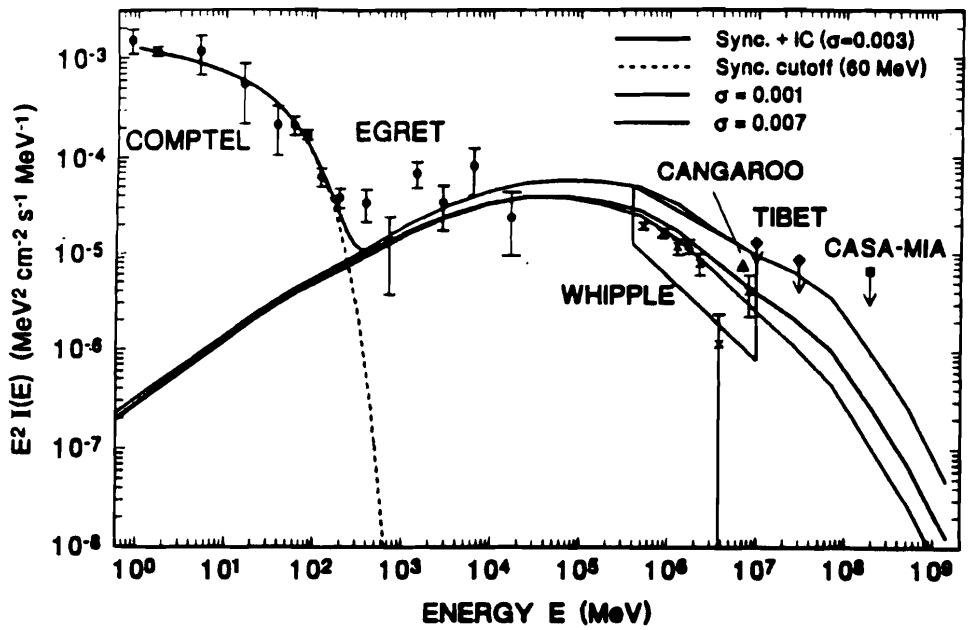

Fig. 8. Observations of the unpulsed photon spectrum from the Crab Nebula. The COMPTEL data are from the PhD thesis of Much (1994); the EGRET data and the model fits are from the work of De Jager *et al.* 1994. The model assumes a population of relativistic electron with energies to 3×10^{15} eV. The σ parameter is the ratio of the magnetic field energy density to the electron energy density.

identify the unidentified members of the COS-B catalog. It is sobering to recognize that there are only two successes from these efforts: Geminga, now identified as a 237 ms pulsar and 2CG342-02, a 102 ms pulsar (PSR 1706-44).

With the publication of the EGRET catalog the problem of the identity of the in-plane sources has been dramatically multiplied. Just as the identity of the COS-B sources was a dominant problem in high energy gamma ray astronomy of the 1980's, one of the themes for the 1990's will surely be the identity of the in-plane EGRET sources. Are they mostly point sources from compact objects like neutron stars? Are they related to supernova remnants where one would expect an enhanced cosmic ray density? Do they correspond to matter enhancements *e.g.* giant molecular clouds being bombarded by cosmic rays of ordinary density? Are they SNOB's (supernova-OB associations)? These are some of the suggestions of the 1980's made in response to COS-B. It is a measure of our slow progress that these same possibilities exist for the EGRET in-plane sources.

Six or seven of the unidentified EGRET sources are sufficiently near to catalogued shell-like SNR that, at least some of them, may be causally linked. *VHE γ-ray astronomy can help in this identification process is several ways.*

In the first place, they can be detected at VHE energies. Several of the EGRET sources which may be identified with SNR have relatively hard spectra which extrapolate to flux levels which are easily detectable at VHE energies. The expected γ-ray fluxes from shell-type SNR have been calculated by Drury, Aharonian, and Völk (1993). The values they calculate support the values extrapolated from EGRET energies. For example, Tycho's SNR, at a distance of 5 kpc, has an expected flux which is ~10% of the Crab, and thus should be detectable by present generation VHE instruments.

Second, the error circle that a VHE imaging detector produces could be significantly smaller than that of the EGRET detector. This is illustrated in figure 9. This tightening of

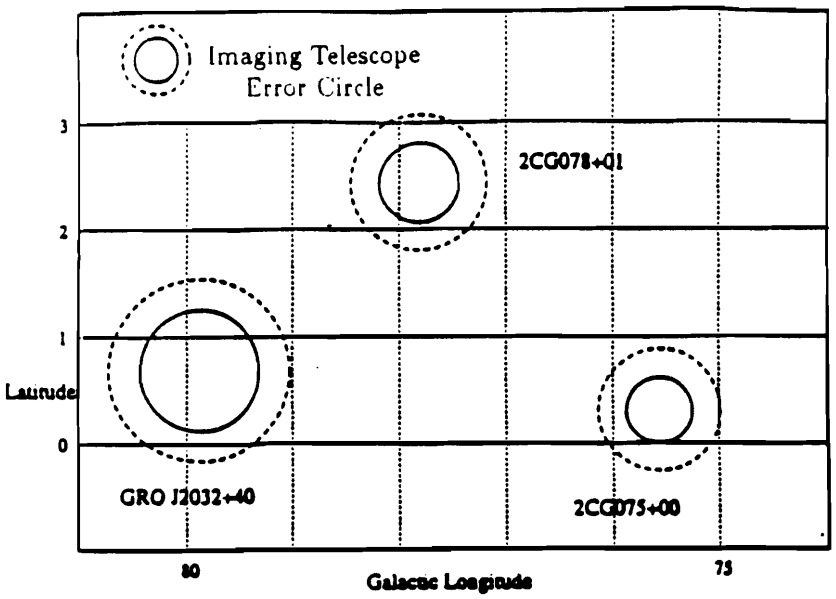

Fig. 9. Map of the Cygnus region of the galactic plane showing the location of three unidentified EGRET sources (Fichtel *et al.* 1994). Around each source two error circles are shown. The inner circle corresponds to the 95% contour given in the EGRET catalog; the outer contour is the sum of the quoted uncertainty plus a systematic uncertainty due to uncertainties in the diffuse background model used. We assume that this uncertainty is 0.3°. Also shown are the significantly smaller error circles associated with a hypothetical detection by an imaging gamma-ray telescope.

the error circle diminishes the probability of a mis-identification. One of the reasons why the error circle at VHE energies may well be smaller than at EGRET energies is that at VHE energies, the confusion from genuinely diffuse galactic emission will be considerably reduced over what is seen at 100 MeV with EGRET, thus the sytematic error in locating the sources which is associated with uncertainties in the diffuse emission should be virtually eliminated. The argument why this is so goes as follows: SNR should contain charged particles having a harder energy spectrum than the observed galactic cosmic ray spectrum, since the galactic cosmic rays have selectively lost their more energetic particles because of their shorter trapping time in the Galaxy. Therefore at the SNR sites there is a harder spectrum of cosmic rays and a harder spectrum of γ-rays. Thus the SNR sources at TeV energies should be relatively stronger than the diffuse γ-ray background than they are at EGRET energies *if they are indeed sources of nucleonic cosmic rays.*

2.6. BATSE - Gamma Ray Bursts

The BATSE detector of the Compton Gamma Ray Observatory has now published a catalog (Fishman *et al.* 1994) giving the details of the first 260 gamma-ray bursts (GRB's). Figure 10 shows the location of an up-dated list of the first 1000 GRB's. As is well known the distribution is remarkably isotropic, with no evidence for structure. Furthermore, the distribution of the intensities of the bursts shows clearly that the BATSE detector is seeing nearly to the "edge" of a three-dimensional distribution. Thus there are only two viable possibilities: either the bursts are cosmologically distant or they form a very large galactic halo population. As the statistics on the bursts continues to increase, this latter possibility looks less and less plausible.

The EGRET team (Dingus *et al.* 1994) has detected several of the GRB's in its spark

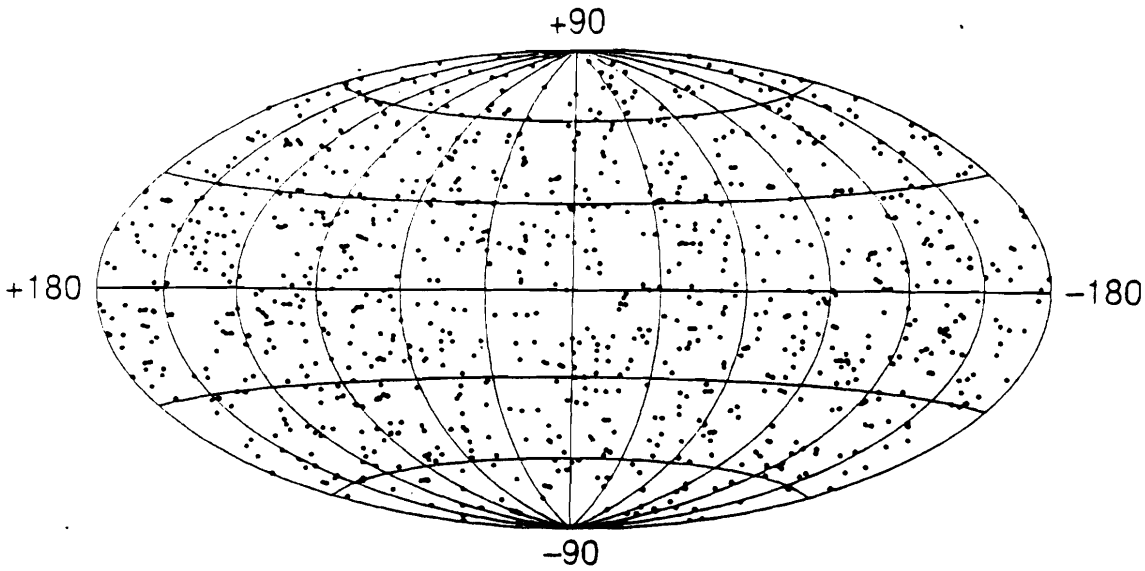

Fig. 10. The distribution on the sky of the first 1000 gamma-ray bursts from the BATSE detector. The first BATSE catalog (Fishman *et al.* 1994) is now published and gives the details on the first 260 GRB's.

chamber and calorimeter. For these few GRB's the power-law differential photon number indices are in the range of -2.0 to -2.5. This suggests that a subset of the GRB's may possibly be detectable at energies above 100 GeV with VHE γ-ray astronomy instruments. If a number of GRB's can be detected at VHE energies and their spectra determined, then the presence or absence of absorption effects (see section 2.4 above) would establish their distance scale in a manner independent of other techniques.

2.7. Sources Which Are Predominantly VHE Emitters

So far, by extrapolating the discoveries of the Compton Gamma Ray Observatory, we have been able to anticipate some of the future scientific discoveries that may be important at VHE photon energies. However, it is possible and perhaps even likely, that VHE γ-ray detectors may detect sources which are not anticipated by virtue of their behavior at other wavelengths.

There are a number of possibilities. For example, it may be that there are TeV analogs of Geminga, a pulsar bright in high energy γ-rays but relatively dim or unseen at other wavelengths. This possibility will only be fully explored when a sensitive all-sky VHE γ-ray survey is made. There may be γ-ray emitting AGN's whose spectral characteristics make them relatively dim at EGRET energies but are bright at VHE energies. Some grand-unification theories postulate the existence of weakly interacting massive particles (WIMP's) whose mass may lie in the 100 GeV to 1 TeV region. The decays of such particles will produce γ-ray spectral features in this same range of energies (Bouquet *et al.* 1989) and would therefore be uniquely the province of VHE γ-ray astronomy.

A high energy γ-ray source which has long been sought at both satellite and ground-based energies, is the final, explosive phase of an evaporating primordial black hole (PBH). PBH's may be expected to form in the early universe from the collapse of portions of the universe with significant overdensities. As time goes on they evaporate (Hawking 1974, Page and Hawking 1976). Given the age of the universe one expects that the PBH's which evaporate today had an initial mass of $\sim 10^{15}$ g. The evaporation concludes with a final burst of a large

today had an initial mass of $\sim 10^{15}$ g. The evaporation concludes with a final burst of a large number of γ-rays (and particles) in a short period of time. The best current limits on the presence of evaporating PBH's come from an air-shower experiment (Alexandreas *et al.* 1993) and atmospheric Cherenkov experiments. Halzen, Zas, MacGibbon, & Weekes (1991) provide a summary of such experiments complete to 1990.

2.8. The Highest Energy Cosmic Rays

There are now several examples of cosmic rays whose energies exceeds 10^{20} eV. Because of photoproduction processes against cosmic microwave background photons, both nuclei and γ-rays with energies greater than $\sim 10^{20}$ eV are severely absorbed for distances above ~ 50 Mpc. One may argue, therefore, that the 2 or 3 events that are greater than 10^{20} eV imply that their point of origin is closer than ~ 50 Mpc. The γ-rays associated with such sources will not suffer any appreciable attenuation up to energies of $\sim 10^{14}$ eV, and therefore may be observable with VHE γ-ray instruments.

3. Conclusions

The purpose of this workshop is to give to the community of VHE γ-ray astronomy direction "towards a major atmospheric Cherenkov detector". From the discussions presented above, what conclusions should we draw about the design requirements for future "major" atmospheric Cherenkov detectors?

Two requirements are: significantly improved sensitivity and substantially lower energy threshold. A reasonable goal for sensitivity is that sources as faint as 1% of the Crab Nebula should be detected at a $\sim 3\sigma$ level within one nights's observation. If present technology is pushed to its limits, this may be feasible. However at energies below 100 GeV the electron cosmic-ray background becomes a major contaminant which may be irreducible. For example, a source 1% as bright as the Crab Nebula has a flux above 100 GeV of $\sim 5 \times 10^{-12}$ photons/cm^2/s. In a 10^4 s observation with a telescope with an effective area of 4×10^8 cm^2 20 photons will be detected. Even if the hadronic cosmic-ray background could be completely eliminated, the electron background (from a solid angle of $\pi(0.08°)^2$) would give an equal number of events. Under these optimistic conditions the source would be detected at the 3.2 σ level. Improved sensitivity is imperative if the VHE γ-ray source list is to be built on a firm foundation of high signal-to-background observations. In addition, improved sensitivity is necessary to study source variability on the shortest possible time scales.

Presently operating detectors have effective thresholds of ~ 250 GeV. In view of the scientific issues discussed above, a threshold of at least 50 GeV or even lower should be a future requirement. The region below the present energy threshold of VHE instruments is a totaly unexplored region of the electromagnetic spectrum.

Two additional requirements stand out: energy resolution and dynamic range. From the discussion of the expected spectral behavior of AGN's, pulsars, and pulsar nebulae, and the presence of spectral modulation due to the intergalactic medium, any new, major atmospheric Cherenkov detector must possess good spectral resolution over a range of photon energies which is sufficient to distinguish a simple power-law from a more complicated spectrum with bumps and cut-offs. If one takes figure 7 as an example of the type of modulation that future Cherenkov detectors should be able to detect, then the dynamic range required is at least 3 orders of magnitude in energy, say 50 GeV to 50 TeV. This will not be easy.

4. References

Antonucci, R. 1993, Ann Rev Astr & Ap, 31, 473.
Bailes, M. & Kniffen, D. A. 1992, ApJ, 391, 659.

Blandford, R. & Levinson, A. 1994, ApJ, submitted.
Bloemen, H. 1993, Proceedings of the 23rd ICRC (Calgary), Rapporteur Vol., 321.
Bouquet, A. *et al.* 1989, Phys Rev D, 40, 3168.
Bregman, J.N. 1992, in Physics of AGN, ed. W. Duschl & S. Wagner (Springer-Verlag), 699.
Chi, X. & Wolfendale, A. W. 1993, J Phys G, 19, 795.
De Jager, O. C. *et al.* 1994, in preparation.
Dermer, C. D. & Schlickeiser, R. 1992, Science, 257, 1642.
Dingus, B. *et al.* 1993, *Gamma Ray Bursts* ed. G. J. Fishman, J. J. Brainerd, & K. Hurley, AIP Conf. Proc. 307, 22.
Dowthwaite, J. C. *et al.* 1984, ApJ, 286, L35.
Drury, L. O'C., Aharonian, F. A. & Völk, H. J. 1993, Proceedings of the 23rd ICRC (Calgary), 1, 455.
Fichtel, C. A. *et al.* 1994, ApJ Suppl. in press.
Fishman, G. J. *et al.* 1994, ApJ Suppl., 92, 229.
Fontaine, G. R. 1993, Proceedings of the workshop, *Towards a Major Atmospheric Cherenkov Detector - II* (Calgary), 12.
Goret, Ph. 1993, Proceedings of the workshop, *Towards a Major Atmospheric Cherenkov Detector - II* (Calgary), 25.
Gould, R. J. & Schréder, G. 1966, Phys Rev Lett, 16, 252.
Halzen, F., Zas, E., MacGibbon, J. H., & Weekes, T. C. 1991, Nature, 353, 807.
Hartman, R. C. *et al.* 1994, *Proc. 2nd Compton Observatory Symposium* ed. C. E. Fichtel, N. Gehrels, & J. P. Norris, AIP Conf. Proc., 304, 563.
Hawking, S. W. 1974, Nature, 248, 30.
Kerrick, A. D. *et al.* 1994, ApJ submitted.
Kifune, T. *et al.* 1994, ApJ in press.
Kniffen, D. A. 1993, Am Scientist, 81, 342.
Lin, Y. C. *et al.* 1992, ApJ, 401, L61.
MacMinn, D. & Primack, J. 1994, ApJ submitted.
Mannheim, K. 1993, A&A, 269, 67.
Marscher, A.P. 1993, in Astrophysical Jets, STScI Symposium Series, 6, ed. D. Burgarella, M. Livio, & C. O'Dea (Cambridge U. Press), 73.
Much, R. 1994, PhD thesis, Max-Planck Institute für Extraterrestriche Physik.
Page, D. N & Hawking, S. P. 1976, ApJ, 206, 1.
Punch, M. *et al.* 1992, Nature, 160, 477.
Raubenheimer, B. C. 1993, Proceedings of the workshop, *Towards a Major Atmospheric Cherenkov Detector - II* (Calgary), 3.
Salamon, M. H., Stecker, F. W., & de Jager 1994, ApJ, 423, L1.
Schubnell, M. S. *et al.* 1994, in preparation.
Shreekumar, P. & Fichtel, C. E. 1991, A&A, 251, 447.
Shreekumar, P. *et al.* 1993, Phys Rev Lett, 70, 127.
Sikora, M., Begelman, M. C., and Rees, M. J. 1994, ApJ, 421, 153.
Stecker, F. W., de Jager, O. C., & Salamon, M. H. 1992, ApJ, 390, L49.
Swanenburg, B. N. it et al. 1981, ApJ, 243, L69.
Teshima, M. 1993, Proceedings of the 23rd ICRC (Calgary), Rapporteur Vol., 257.
Vacanti, G. et al. 1991, ApJ, 377, 467.
Zdardiski, A. A. & Krolik, J. H. 1993, ApJ, 409, L33.